

OFFICE OF NAVAL RESEARCH  
CONTRACT N00014-94-C-0149

TECHNICAL REPORT 96-04

THERMAL AND CARDIOVASCULAR STRAIN FROM HYPOHYDRATION:  
INFLUENCE OF EXERCISE INTENSITY

BY

S.J. MONTAIN, M.N. SAWKA, W. LATZKA, AND C.R. VALERI

NAVAL BLOOD RESEARCH LABORATORY  
BOSTON UNIVERSITY SCHOOL OF MEDICINE  
615 ALBANY STREET  
BOSTON, MA 02118

11 JULY 1996

19990225009

Reproduction in whole or in part is permitted for any purpose of  
the United States Government.

Distribution of this report is unlimited.

**ABSTRACT**

This study determined the effects of exercise intensity on the physiologic (thermal and cardiovascular) strain induced from hypohydration during heat stress. We hypothesized that the added thermal and cardiovascular strain induced by hypohydration would be greater during high intensity than low intensity exercise. Nine heat-acclimated men completed a matrix of nine trials: three exercise intensities, 25%, 45% and 65%  $\dot{V}O_{2\max}$ ; and three hydration levels, euhydration and hypohydration at 3% and 5% body weight loss (BWL). During each trial, subjects attempted 50 min of treadmill exercise in a hot room (30°C db, 50% rh) while body temperatures and cardiac output were measured. Hypohydration was achieved by exercise and fluid restriction the day preceeding the trials. Core temperature increased ( $P<0.05$ ) 0.12°C per %BWL at each hypohydration level and was not affected by exercise intensity. Cardiac output was reduced ( $P<0.05$ ) compared to euhydration levels and was reduced more during high compared to low intensity exercise after 5% BWL. It was concluded that: a) the thermal penalty (core temperature increase) accompanying hypohydration is not altered by exercise intensity; and b) at severe hypohydration levels, the cardiovascular penalty (cardiac output reduction) increases with exercise intensity.

**Keywords:** dehydration, stroke volume, cardiac output, thermoregulation

## INTRODUCTION

Persons performing physical activity while hypohydrated (reduced total body water) have increased physiologic strain (9,19), degraded performance (2,17) and increased susceptibility to heat injury / illness (20). During hot weather, fluid balance is an important issue because the hot climate greatly increases fluid requirements (8), and hypohydration's adverse effects are greater during exercise combined with climatic heat stress than during exercise stress alone (15,18). Most individuals perform prolonged exercise under some level of hypohydration, with some losing up to 6% of their pre-exercise body weight during activity (15,17). Since athletic events and occupational tasks require a range of exercise intensities (from ~25% to > than 100%  $\text{VO}_{2\text{max}}$ ) it is important to consider whether the exercise intensity (metabolic rate) will modify the adverse effects of hypohydration. While several studies have described the physiologic responses to different hypohydration levels, no study has examined whether exercise intensity modifies the physiologic burden imposed by hypohydration.

The purpose of this study was to determine the effects of exercise intensity on the physiologic (thermal and cardiovascular) strain induced by hypohydration during heat stress. Body temperatures and cardiac output were measured during a matrix of exercise and hydration conditions which will be encountered during athletic events and many occupational tasks. We hypothesized that the added thermal and cardiovascular strain induced by hypohydration would be greater as exercise intensity increased. This hypothesis was based on our observation that hypohydration induced a smaller core temperature increase (above euhydration levels) in studies where volunteers performed low intensity exercise compared to other studies where volunteers performed higher intensity exercise (17).

## METHODS

*Subjects.* Nine healthy heat acclimated men participated in this study. They had a mean $\pm$ SD age of  $24\pm 6$  yr, height of  $176\pm 8$  cm, body weight  $80.5\pm 13.7$  kg, and maximal oxygen uptake ( $\dot{V}O_{2\max}$ ) of  $56.5\pm 6.8$  ml $\cdot$ kg $^{-1}\cdot$ min $^{-1}$ . All subjects gave their voluntary and informed consent to participate in this experiment which was approved by the appropriate Institutional Review Boards. Other results from this study have been published (10,11).

*Experimental Protocol.* Prior to experimental testing each subject's  $\dot{V}O_{2\max}$  was determined by an incremental treadmill test (21). In addition, during the 2 week period preceding experimental testing, nude body weights were measured daily to establish baseline body weights that represented euhydration for each subject. These body weights were taken in the morning after voiding and prior to breakfast. Additional nude body weights were also taken periodically during testing to adjust for body weight changes over time.

The subjects were heat acclimated by walking (30-40%  $\dot{V}O_{2\max}$ ) for two 50-min exercise bouts separated by 10 min rest in the heat (40°C db, 20% rh or 35°C db, 75% rh) on 10 occasions during a 12 day period. Water was available ad libitum during the exercise sessions. Within 3 days of completing the heat acclimation protocol, the experimental trials were initiated. The subjects then completed 9 experimental trials in random order consisting of 50 min of treadmill exercise in a hot climate (30°C db, 50% rh, wind speed 1 m $\cdot$ s $^{-1}$ ; WBGT =  $\sim 26^\circ\text{C}$ ). During each trial the subjects exercised at either 25% (low intensity), 45% (moderate intensity) or 65% (high intensity) of their individual  $\dot{V}O_{2\max}$  when hypohydrated by either 0%, 3% or 5% of their baseline body weight. Generally, two tests were performed per week, with a minimum

of one week separating the 5% hypohydration trials. The trial order was varied to minimize any effects of trial order. The trials were terminated if predetermined end-points of heart rate (95% maximum heart rate) or core temperature ( $39.5^{\circ}\text{C}$ ) were achieved. The subjects wore only shorts, socks and athletic shoes during exercise. Three hundred ml of warm water ( $37^{\circ}\text{C}$ ) were provided at 20 min of exercise to offset water lost through sweating.

Hypohydration was achieved the day before each trial, using a standardized exercise-heat protocol (11,18-20) in which the volunteers either drank in proportion to the level of hypohydration desired or did not drink to replace sweat losses. All subjects completed the dehydration sessions 12-15 h prior to the experimental tests and spent the night resting in a temperate climate. During the rest and/or sleeping period, food and fluid intake were available if body weight was below the desired level. Fluids were restricted if body weight was not below the desired level. The subjects were instructed to standardize their food and fluid intake during the 48 h period preceding each trial. Upon awakening, subjects were given 200 ml of 100% fruit juice to standardize fluid intake the morning of the experimental test.

*Experimental Procedures.* Core (esophageal,  $T_{\text{es}}$ ) and skin temperature were recorded at one minute intervals. Skin temperatures were measured at 4 sites (forearm, chest, thigh and calf) and mean weighted skin temperature ( $T_{\text{sk}}$ ) calculated (13). Mean body temperature was calculated using a 9:1  $T_{\text{es}}$  to  $T_{\text{sk}}$  weighting. Average  $T_{\text{es}}$  was calculated by averaging the respective temperatures measured over the final 20 min of exercise. This time period was chosen as it avoided the rapid rise of core temperature which occurred during the first 20 min of exercise. If a trial was discontinued early, average  $T_{\text{es}}$  was calculated from 30 min to end of exercise and the same endpoint time was used to calculate average  $T_{\text{es}}$  and  $T_{\text{b}}$  for the other

1 hydration levels at that exercise intensity.

2 Oxygen uptake and carbon dioxide production were determined via open circuit  
3 spirometry (Model 2900, Sensormedics Corp., Yorba Linda, CA) prior to each measurement of  
4 cardiac output. Cardiac output was measured in triplicate, at 3 min intervals after 6 min and 36  
5 min of exercise using a CO<sub>2</sub> rebreathing technique (6). Estimates of CO<sub>2</sub> content were corrected  
6 for hemoglobin concentration.

7 Blood samples were obtained from an indwelling Teflon catheter placed within a  
8 superficial forearm vein. Blood samples were obtained at rest following 15 min of quiet standing  
9 in the warm environment, at 20 min of exercise and during the final minute of exercise.

10 Hemoglobin concentration was measured in duplicate with a Hemoglobinometer (Coulter  
11 Electronics Inc., Hialeah, FL). Plasma osmolality was measured in triplicate by freezing point  
12 depression (Precisions Systems Inc., Natick, MA).

13 Plasma volume and erythrocyte volume were measured on one occasion by the <sup>125</sup>I-  
14 labeled albumin and the <sup>51</sup>Cr methods (21), respectively. Blood volume was calculated as the  
15 sum of the plasma volume and erythrocyte volume. Percent changes in blood volume were  
16 calculated from hemoglobin and hematocrit (7). The absolute blood and plasma volumes were  
17 calculated by adjusting the measured resting blood by the percent changes in hemoglobin and  
18 hematocrit.

19 *Statistical Analysis.* The independent effect of hydration on physiologic responses at  
20 each exercise intensity were analyzed using 2 way repeated measures analysis of variance. The  
21 independent effect of exercise intensity on the core temperature responses when euhydrated were  
22 analyzed using 2 way repeated measures analysis of variance. The effect of exercise intensity on

the added thermal and cardiovascular strain at each hypohydration level were analyzed using both 1- and 2-way analysis of variance. Statistical significance was tested at the  $P < 0.05$  level. Tukey's HSD procedure was used to identify differences between means when statistical significance was achieved. Data are presented in text as mean $\pm$ sd. Preliminary power analyses (power = 0.8,  $r=0.8$ ) indicated that 7 subjects should have been sufficient to detect an effect size of  $0.2^{\circ}\text{C}$ .

## RESULTS

All subjects completed 50 min of exercise during the low and moderate intensity exercise trials. During the high intensity trials, however, 19 of 27 experiments were stopped prior to 50 min exercise due to attainment of medical endpoint criteria for heart rate (95% HRmax) and/or core temperature ( $39.5^{\circ}\text{C}$ ) levels. As a result, 9 of 27 experiments lacked cardiac output measurements at 40 min of exercise. Hypohydration did not alter ( $P>0.05$ )  $\dot{V}\text{O}_2$ , pulmonary ventilation or ventilatory equivalent of oxygen.

*Body Weight.* Preexercise body weights ( $P<0.05$ ) were  $80.5\pm13.7$ ,  $78.2\pm13.5$ , and  $76.6\pm13.5$  kg for the euhydration and for the 3 and 5% hypohydration trials, respectively, and were similar ( $P>0.05$ ) across all exercise intensity trials. The body weight losses (BWL) were  $2.8\pm0.8$  and  $4.9\pm1.1\%$  for the 3 and 5% BWL trials, respectively.

*Body Temperature Responses.* Resting  $T_{\text{es}}$  when euhydrated were  $36.8\pm0.2$ ,  $36.8\pm0.4$ ,  $36.8\pm0.3^{\circ}\text{C}$  for 25%, 45% and 65%  $\dot{V}\text{O}_2\text{max}$  trials, respectively. Resting  $T_{\text{es}}$  after 3% BWL were  $36.7\pm0.3$ ,  $36.8\pm0.3$  and  $37.0\pm0.4^{\circ}\text{C}$  for 25%, 45% and 65%  $\dot{V}\text{O}_2\text{max}$  exercise, respectively. Resting  $T_{\text{es}}$  after 5% BWL were  $37.0\pm0.3$ ,  $37.0\pm0.4$  and  $37.0\pm0.4^{\circ}\text{C}$  for 25%, 45% and 65%

1  $\text{VO}_{2\text{max}}$  exercise, respectively.

2 When euhydrated,  $T_{\text{es}}$  increased ( $P<0.05$ ) with exercise intensity (Figure 1a).

3 Hypohydration increased ( $P<0.05$ ) the  $T_{\text{es}}$  response to exercise and the magnitude of the  $T_{\text{es}}$   
4 increment was graded with the hypohydration level (Figure 1b). To examine the effect of  
5 exercise intensity on the  $T_{\text{es}}$  increment accompanying hypohydration, the  $T_{\text{es}}$  responses were  
6 normalized to resting temperature values and the difference in temperature between 3% and 5%  
7 BWL relative to 0% BWL trials calculated for each exercise time point. Due to subject attrition  
8 during the 65%  $\text{VO}_{2\text{max}}$  trials, statistical comparisons across the 3 exercise intensities were  
9 limited to the first 30 min of exercise. Two-way analysis of variance (intensity x time) at each  
10 hypohydration level demonstrated no difference ( $P<0.05$ ) in  $T_{\text{es}}$  increment across exercise  
11 intensities. Mean skin temperature averaged  $0.6^{\circ}\text{C}$  higher ( $P<0.05$ ) than when euhydrated during  
12 low intensity exercise at 5% BWL. The  $T_{\text{sk}}$  responses were similar ( $P>0.05$ ) across hydration  
13 levels during 45% and 65%  $\text{VO}_{2\text{max}}$  exercise. Mean body temperatures increased ( $P<0.05$ ) with  
14 exercise intensity and hypohydration level. The  $T_{\text{b}}$  increase above euhydration was within  $0.1^{\circ}\text{C}$   
15 across all exercise intensities for both hypohydration levels.

16 *Cardiovascular Responses.* Heart rate increased ( $P<0.05$ ) with exercise intensity  
17 averaging  $95\pm 7$ ,  $119\pm 6$ , and  $149\pm 9$  bpm at 10 min of exercise and  $98\pm 7$ ,  $125\pm 6$ , and  $167\pm 14$  bpm  
18 at 40 min of exercise when euhydrated, respectively. Hypohydration increased ( $P<0.05$ ) heart  
19 rate above euhydration levels during moderate and high intensity exercise. Statistical analysis of  
20 the effect of exercise intensity on heart rate elevations (above euhydration) revealed that there  
21 were differences ( $P<0.05$ ) between exercise intensities at 3% BWL but the chosen post hoc  
22 procedure was unable to discriminate differences amongst the mean values (Figure 2). At 5%



1 BWL, the heart rate elevations were similar ( $P>0.05$ ) across all exercise intensities.

2 Stroke volume averaged  $145\pm 29$ ,  $136\pm 14$ , and  $131\pm 15$  ml at 10 min of exercise and  
3  $142\pm 25$ ,  $130\pm 11$ , and  $119\pm 18$  ml at 40 min of exercise when euhydrated during 25%, 45% and  
4 65%  $\dot{V}O_{2\max}$  trials, respectively. Hypohydration lowered ( $P<0.05$ ) stroke volume at all exercise  
5 intensities. The stroke volume reductions (below euhydration) were not altered ( $P>0.05$ ) by  
6 exercise intensity at either hypohydration level (Figure 2).

7 Cardiac output increased ( $P<0.05$ ) with exercise intensity when euhydrated averaging  
8  $13.6\pm 2.4$ ,  $15.9\pm 1.6$ , and  $19.4\pm 1.8$  L/min at 10 min of exercise and  $13.7\pm 2.0$ ,  $16.1\pm 1.5$ , and  
9  $19.7\pm 2.5$  L/min at 40 min of exercise, respectively. Hypohydration reduced ( $P<0.05$ ) cardiac  
10 output during 45% and 65%  $\dot{V}O_{2\max}$  exercise. While hypohydration tended to lower cardiac  
11 output during 25%  $\dot{V}O_{2\max}$  exercise the reductions were not statistically significant ( $P<0.10$ ).  
12 The magnitude of cardiac output reductions from euhydration levels increased with exercise  
13 intensity (Figure 2) at 5%BWL ( $P<0.05$ ) but did not achieve statistical significance at 3% BWL  
14 ( $P<0.2$ ).

15 *Blood parameters.* Plasma osmolality increased ( $P<0.05$ ) progressively with  
16 hypohydration level (0%= $284\pm 5$ ; 3%= $289\pm 6$ ; 5%= $295\pm 5$  mosm/kg) and increased ( $P<0.05$ ) with  
17 exercise intensity. Exercise intensity, however, did not alter ( $P>0.05$ ) the magnitude of  
18 osmolality increase accompanying hypohydration. Blood volume decreased progressively  
19 ( $P<0.05$ ) with hypohydration level (0%= $5.17\pm 0.56$ ; 3%= $5.04\pm 0.64$ ; 5%= $4.96\pm 0.56$  L). Exercise  
20 intensity did not modify ( $P>0.05$ ) the magnitude of blood volume decrease associated with  
21 hypohydration.  
22

## DISCUSSION

This study determined whether the physiologic impact of hypohydration during exercise-heat stress becomes more severe with higher exercise intensity. Previous research had identified heat acclimation state (4,18) and aerobic fitness (4,5) as factors influencing the magnitude of thermal penalty associated with hypohydration during exercise-heat stress. In this study, these factors were controlled by heat acclimating the subjects and using relative exercise intensities. The exercise intensities ranged from 25% to 65% of maximal aerobic power; similar to many athletic and occupational tasks. It is acknowledged that some athletic events require higher relative exercise intensities, however, their use would have resulted in uncompensable heat stress (12) and exhaustion occurring before steady-state physiologic responses could be obtained. We chose to employ a hypohydration approach (fluid loss prior to exercise) rather than a progressive dehydration approach, to avoid the confounding influences of exercise time and changing hydration levels. By controlling the method of water loss, the magnitude of water loss (i.e., similar body weight loss, hypertonicity, hypovolemia), the climatic conditions, and using a repeated measures study design, we were able to directly assess the effects of exercise intensity on the physiologic penalty induced by hypohydration during heat stress.

We found that exercise intensity had little effect on the thermal penalty (core temperature elevation) associated with hypohydration. The three exercise intensities produced similar  $T_{es}$  increments after both 3% and 5%BWL. Although there was a tendency for a smaller thermal penalty after 5% BWL when performing low intensity exercise, the magnitude of the difference did not achieve statistical significance. Furthermore, when differences in mean skin temperature between trials were accounted for by calculation of mean body temperature, the thermal

1 responses to 5% BWL became more similar, supporting the conclusion that the low exercise  
2 intensity had little impact on the thermal penalty accompanying hypohydration. At 3% and 5%  
3 BWL, core temperature increased by  $0.12^{\circ}\text{C}$  per %BWL across the three exercise intensities.  
4 These hypohydration mediated core temperature elevations are comparable to other published  
5 values (19,23).

6 The cardiovascular (cardiac output reduction) penalty imposed by hypohydration  
7 generally became larger as exercise intensity increased, particularly at high levels of fluid loss.  
8 This finding suggests that hypohydrated athletes performing high intensity exercise might be at  
9 greater risk for physical performance degradation than those performing low intensity exercise in  
10 the heat. The rationale for this statement is that during high intensity exercise,  $a-\bar{v}\text{O}_2$  differences  
11 are close to maximum so any cardiac output reduction will make it difficult to maintain the  
12 required oxygen uptake (3). Sawka and colleagues (16) demonstrated this in hypohydrated  
13 runners during high intensity prolonged exercise. They showed that cardiac output declined over  
14 time and that  $a-\bar{v}\text{O}_2$  difference widened to maximum values at the point subjects were unable to  
15 maintain pace. During lower intensity exercise, even if hypohydration causes a cardiac output  
16 reduction, the  $a-\bar{v}\text{O}_2$  difference can widen to achieve the oxygen uptake required to maintain  
17 performance.

18 The magnitude and pattern of cardiovascular responses observed in this study agree with  
19 those previously reported for hypohydrated subjects during exercise (1,14,22). Only Saltin (14),  
20 however, had previously examined the influence of exercise intensity in hypohydrated subjects.  
21 That study was not performed in the heat and lacked sufficient numbers of subjects to  
22 statistically evaluate the data. Examination of the individual data, however, suggests that stroke

1 volume declined and heart rate increased similarly whether exercising at 45% or 77%  $\dot{V}O_{2\max}$   
2 when hypohydrated.

3 One potentially confounding factor in this study was the use of the same wind velocity at  
4 each exercise intensity. The wind speed used (0.9 m/sec) was insufficient to prevent thermal and  
5 cardiovascular drift during the high exercise intensity, and 18 of the 27 trials at 65%  $\dot{V}O_{2\max}$   
6 were terminated due to achievement of 95% maximal heart rate. To determine whether this  
7 thermal and cardiovascular drift reduced the magnitude of body temperature and heart rate  
8 increase attributable to hypohydration, three of the subjects repeated the high intensity exercise  
9 when euhydrated and after 5% BWL when wind velocity was increased to 2.5-3.0 m/sec.  
10 Despite attenuating thermal and cardiovascular drift, the core temperature and heart rate increase  
11 ( $T_{es}=0.12^{\circ}\text{C} / \% \text{BWL}$ ; heart rate=3 beats /  $\% \text{BWL}$ ) attributable to hypohydration were similar to  
12 the values obtained at the low wind speed. Therefore, it is unlikely that the low wind speed  
13 biased our results.

14 This study determined the effects of exercise intensity on physiologic (thermal and  
15 cardiovascular) strain induced by hypohydration during heat stress. We found that the exercise  
16 intensity had no effect on the thermal penalty imposed by hypohydration, but high intensity  
17 exercise was associated with a greater cardiovascular penalty after 5%BWL. These results  
18 indicate that in hot climates, hypohydration might degrade physical performance more during  
19 physical activities requiring high intensity than low intensity exercise thus further emphasizing  
20 the need for maintenance of body hydration with intensive exercise.  
21

**ACKNOWLEDGMENTS**

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, or decision, unless so designated by other official documentation. The authors were employees of the US federal government when this work was investigated and prepared for publication; therefore, it is not protected by the Copyright Act and there is no copyright of which the ownership can be transferred.

The authors thank James E. Kain, Brent S. Mair, Catherine O'Brien and Gerald R. Shoda for their technical assistance.

## 1 REFERENCES

2 <sup>1</sup>Allen T.E., Smith D.P., Miller D.K. Hemodynamic response to submaximal exercise after  
3 dehydration and rehydration in high school wrestlers. *Med Sci Sports* 9: 159-163, 1977.

4  
5 <sup>2</sup>Armstrong L.E., Costill D.L., Fink W.J. Influence of diuretic-induced dehydration on  
6 competitive running performance. *Med Sci Sports Exerc* 17: 456-461, 1985.

7  
8 <sup>3</sup>Åstrand P.-O., Rodahl K. Textbook of Work Physiology, 2nd: New York, McGraw-Hill, Inc.  
9 1977.

10  
11 <sup>4</sup>Buskirk E.R., Impietro P.F., Bass D.E. Work performance after dehydration: effects of physical  
12 conditioning and heat acclimatization. *J Appl Physiol* 12: 189-194, 1958.

13  
14 <sup>5</sup>Cadarette B.S., Sawka M.N., Toner M.M., Pandolf K.B. Aerobic fitness and the hypohydration  
15 response to exercise-heat stress. *Aviat Space Environ Med* 55: 507-512, 1984.

16  
17 <sup>6</sup>Defares J.G. Determination of mixed venous CO<sub>2</sub> tensions from the exponential CO<sub>2</sub> rise during  
18 rebreathing. *J Appl Physiol* 13: 159-164, 1958.

19  
20 <sup>7</sup>Dill D.B., Costill D.L. Calculation of percentage changes in volumes of blood, plasma, and red  
21 cells in dehydration. *J Appl Physiol* 37: 247-248, 1974.  
22

<sup>8</sup>Greenleaf J.E. Environmental issues that influence intake of replacement beverages, in Marriott B.M.(ed.): Fluid Replacement and Heat Stress. Washington, D.C. National Academy Press, 1994, pp 195-214.

<sup>9</sup>Montain S.J., Coyle E.F. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J Appl Physiol* 73: 1340-1350, 1992.

<sup>10</sup>Montain S.J., Laird J.E., Latzka W.A., Sawka M.N. Aldosterone and vasopressin responses in the heat: hydration level and exercise intensity effects. *Med Sci Sports Exerc* 29: 661-668, 1997.

<sup>11</sup>Montain S.J., Latzka W.A., Sawka M.N. Control of thermoregulatory sweating is altered by hydration level and exercise intensity. *J Appl Physiol* 79: 1434-1439, 1995.

<sup>12</sup>Montain S.J., Sawka M.N., Cadarette B.S., Quigley M.D., McKay J.M. Physiological tolerance to uncompensable heat stress: effect of exercise intensity, protective clothing and climate. *J Appl Physiol* 77: 216-222, 1994.

<sup>13</sup>Ramanathan N.L. A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 19: 531-533, 1964.

<sup>14</sup>Saltin B. Circulatory response to submaximal and maximal exercise after thermal dehydration. *J Appl Physiol* 19: 1125-1132, 1964.

<sup>15</sup>Sawka M.N. Physiological consequences of hypohydration: exercise performance and thermoregulation. *Med Sci Sports Exerc* 24: 657-670, 1992.

<sup>16</sup>Sawka M.N., Knowlton R.G., Critz J.B. Thermal and circulatory responses to repeated bouts of prolonged running. *Med Sci Sports* 11: 177-180, 1979.

<sup>17</sup>Sawka M.N., Montain S.J., Latzka W.A. Body Fluid Balance During Exercise-Heat Exposure, in Buskirk E.R., Puhl S.M.(eds.): *Body Fluid Balance: Exercise and Sport*. Boca Raton, CRC Press, Inc. 1996, pp 143-161.

<sup>18</sup>Sawka M.N., Toner M.M., Francesconi R.P., Pandolf K.B. Hypohydration and exercise: effects of heat acclimation, gender, and environment. *J Appl Physiol* 55: 1147-1153, 1983.

<sup>19</sup>Sawka M.N., Young A.J., Francesconi R.P., Muza S.R., Pandolf K.B. Thermoregulatory and blood responses during exercise at graded hypohydration levels. *J Appl Physiol* 59: 1394-1401, 1985.

<sup>20</sup>Sawka M.N., Young A.J., Latzka W.A., Neuffer P.D., Quigley M.D., Pandolf K.B. Human tolerance to heat strain during exercise: influence of hydration. *J Appl Physiol* 73: 368-375, 1992.

<sup>21</sup>Sawka M.N., Young A.J., Pandolf K.B., Dennis R.C., Valeri C.R. Erythrocyte, plasma, and



1 blood volume of healthy young men. *Med Sci Sports Exerc* 24: 447-453, 1992.

2  
3 <sup>22</sup>Sproles C.B., Smith D.P., Byrd R.J., Allen T.E. Circulatory responses to submaximal exercise  
4 after dehydration and rehydration. *J Sports Med* 16: 98-105, 1976.

5  
6 <sup>23</sup>Strydom N.B., Holdsworth L.D. The effects of different levels of water deficit on physiological  
7 responses during heat stress. *Int Z angew Physiol einsch Arbeitsphysiol* 26: 95-102, 1968.

## FIGURE LEGENDS

**Figure 1.** Left plot - Esophageal temperature ( $T_{es}$ ) responses during exercise at 25%, 45% and 65%  $\dot{V}O_{2max}$  when euhydrated (0% BWL). Right plot -  $T_{es}$  increment accompanying 3% BWL (shaded symbols) and 5% BWL (open symbols) when exercising at 25%, 45% and 65%  $\dot{V}O_{2max}$ . The  $T_{es}$  increment accompanying 5% BWL was greater ( $P < 0.05$ ) than 3% BWL. Data are means  $\pm$  se for nine subjects except  $n = 8$  subjects at 30 min exercise during 65%  $\dot{V}O_{2max}$  trials after 3% and 5% BWL. \* Greater than 25%  $\dot{V}O_{2max}$ . † Greater than 45%  $\dot{V}O_{2max}$ .

**Figure 2.** Cardiovascular changes due to hypohydration (3% & 5% BWL) during low, moderate and high intensity exercise. Data are means  $\pm$  se for 9 subjects for heart rate and 8 subjects for cardiac output and stroke volume with exception that  $n = 6$  at 40 min during 65%  $\dot{V}O_{2max}$  trial with 3% BWL. \* Different than 65%  $\dot{V}O_{2max}$ .



